Wind and Solar Energy Droughts:
Potential Impacts on Energy System Dynamics and Research Needs

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Why study Wind and Solar Droughts (WSDs/Dunkelflaute)?

- To be reliable, a wind and solar-based energy system must function during the times of greatest system stress, or net energy droughts (wind and solar droughts, in conjunction with large loads).

- If an energy system design can handle the worst net energy droughts, it will function during periods of more normal generation and load.

- Thus, net energy droughts ultimately determine energy system design, and WSDs are the major component of these net energy droughts.

Presentation based on three papers:

- Wilczak, J.M, E. Akish, A. Capotondi, G.P. Compo, 2024: Evaluation and bias correction of the ERA5 reanalysis over the United States for wind and solar energy applications. Energies, 17(7) 1667. https://doi.org/10.3390/en17071667
- Wilczak, J.M, E. Akish, A. Capotondi, G.P. Compo, A. Hoell, 2024: A multidecadal analysis of U.S. and Canadian wind and solar energy droughts. J. Renewable Sustainable Energy 16. https://doi.org/10.1063/5.0219648
- Wilczak, J. M., D. Kirk-Davidoff, H. Bloomfield, C. Bracken, J. Sharp, 2025: Wind and solar energy droughts: Potential impacts on energy system dynamics ad research needs. J. Renewable Sustainable Energ. https://doi.org/10.1063/5.0253058 .

OUTLINE

Definitions
Metrics

10 topical areas where research is needed:

1) Linking WSDs to CE models.
2) Classifying meteorological regimes producing droughts
3) Snow and ice solar droughts
4) Creation of more accurate, higher spatial resolution, longer time-span reanalysis datasets.
5) Evaluation of accuracy of NSRDB, SARAH for WSDs.
6) Evaluation of the impact of W&S flood events on system design and market design
7) WSD limits of predictability
8) WSD implications for demand response programs
9) Climate modes of variability, and climate change impacts
10) Developing countries

Definitions

- Multi-dimensional, four main attributes of Dunkelflaute: intensity, duration, spatial extent, and recurrence intervals.

- Seasonal effects:
  - Defined relative to the seasonally varying mean production
    - removes the mean seasonal variation leaving only short-term weather and interannual climate variations

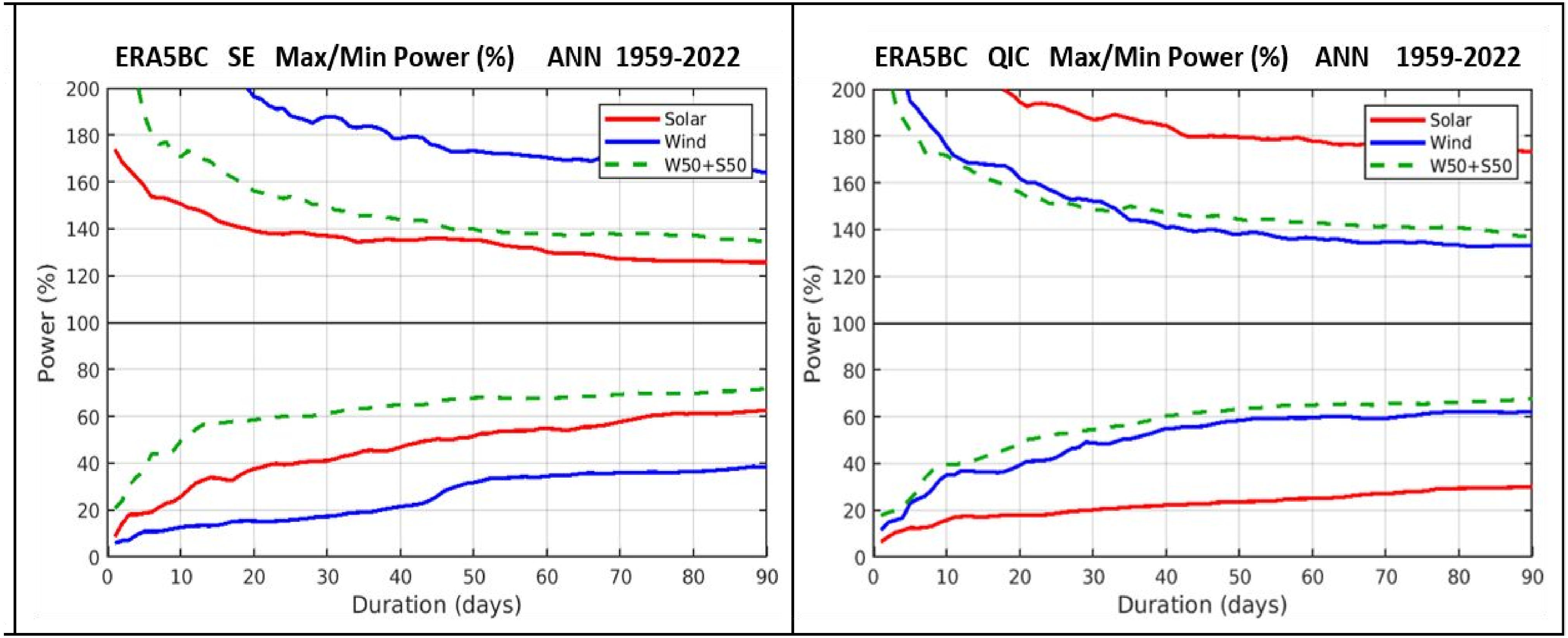
  - Defined relative to the long-term, multi-decadal mean production.
    - Includes the seasonal variations.
    - useful if one wishes to analyze the impact of droughts on the energy system, as the system must be responsive to the total energy generation shortage, no matter what its source.

Metrics (1) –IDF Curves

Droughts often defined using ad-hoc thresholds of duration or amplitude, but these have no clear relation to the energy system. Ideally, drought metrics should depend only on energy system attributes.

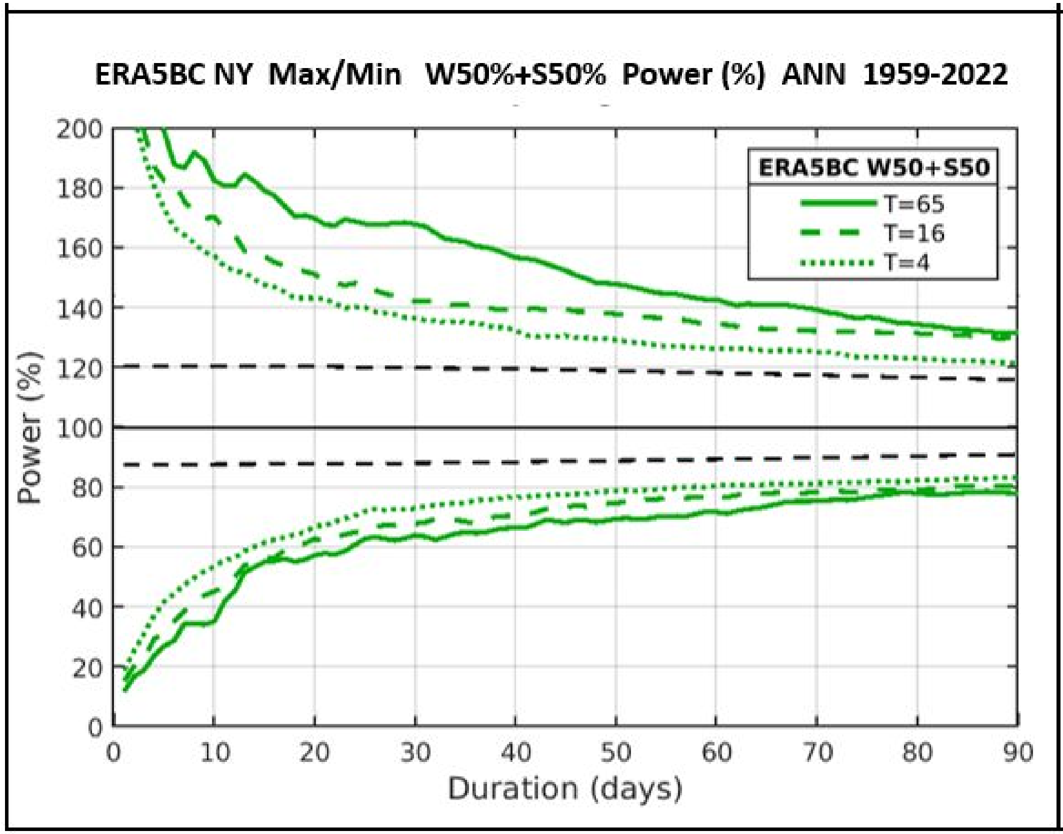
Preferred metric: threshold-free Intensity-Duration-Frequency (IDF) diagrams , shown here for SE/QIC ERA5BC daily CF values.

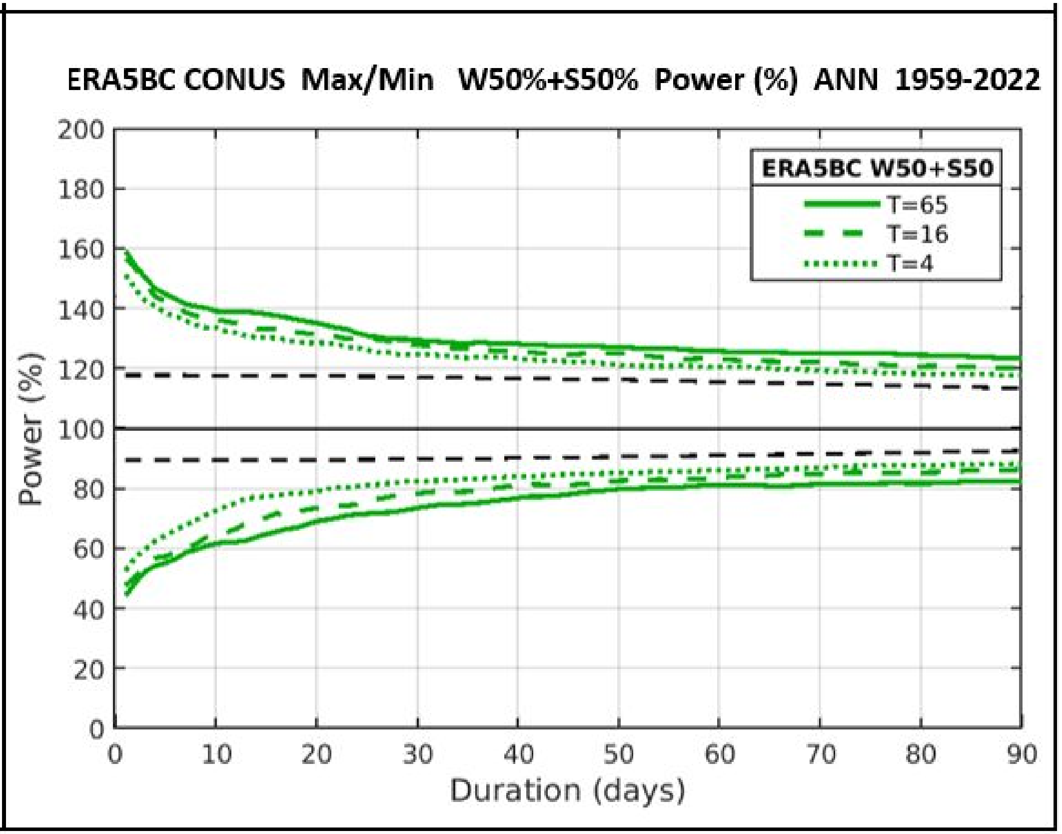
1) Normalize timeseries of CFs by mean CF, shown as a percent.
2) Apply moving averages, longest averaging length corresponds to maximum duration drought of interest
3) Find and plot min and max event for each duration. 0-100% = droughts, >100% = floods.



Metrics (2) – Recurrence Intervals

- For each duration value, the most extreme event is removed, and the next most extreme value is found.
- Empirical recurrence intervals can be readily found from this family of ranked extreme events.
- Energy balance droughts defined in this way are prescribed in terms of an attribute of the energy system, that is, the tolerance of the grid (or society) to accept these shortages at some frequency of occurrence, and mitigate them through a combination of energy storage, demand response, dispatchable generation, or load shedding.





WSD mitigation options in highly renewable systems

WSDs will be mitigated through a combination of

- Overbuilding of generation capacity
- Transmission
- Energy storage
- Dispatchable generation (fossil fuel, hydropower, nuclear, geothermal).
- Demand response

Finding the optimal mix of these mitigation approaches is studied using capacity expansion (CE) models, using assumed future levels of energy demand.

Research Need 1: Linking WSDs to CE models.

- Relatively few CE model studies have been published.
- Most often, they use unverified meteorological data sets. Are their biases sufficiently small to accurately characterize Dunkelflaute?
- Too short of time periods used. (Typically, only 1-7 years of data.)
- Related: Don’t include analysis of drought recurrence intervals.
- Very few, if any, CE model studies that investigate in detail how the energy system responds to WSDs. Do different CE models mitigate droughts in similar or very different ways?

Research Need 2: Meteorological conditions producing WSDs

- Wind energy droughts: persistent high surface pressure over a large region, often associated with blocking highs.

- Solar energy droughts: protracted periods of cloud cover, which can be associated with low-pressure systems, or with fog and low clouds that occur in some high-pressure regimes.

- Compound energy supply droughts: combine weak winds with cloudy days, and the exact meteorological conditions of most importance will depend on the ratio of installed wind and solar generation capacity.

- Energy balance droughts that combine weak winds, cloudy days, and either hot or cold temperatures may stress the system the most.

- Some work has been done to classify meteorological conditions during Dunkelflaute events in Europe, relating wind droughts to Scandinavian blocking highs. This is an area where much more could be done, given the likely significant regional variability in meteorological drivers of energy droughts.

Research Need 3: Snow and ice, wild fires, dust storms.

- Ice accumulation on wind turbine blades also can result in significant power reductions, of up to 80% even in high wind conditions, and can cover large geographic areas at times when energy demand is high.

- Snow and ice on solar panels, no mention in CE model studies.

Research Need 4: Better data sets: multi-decadal, highres (~3km), bias-corrected reanalyses of consistent wind and solar fields.

- Reanalysis datasets (MERRA, ERA5, WindToolkit).
  - Assimilate observations, often considered to represent the true state of wind and solar energy generation. Because they are dependent on an NWP model, they too have errors,
  - Especially true for extreme WSDs. For example, Wilczak et al. (2004) showed that over the United States
    - the ERA5-derived solar power produced during the most extreme 10-day duration droughts was 62% greater than that derived directly from solar irradiance observations;
    - the most extreme wind droughts at some sites even in flat terrain, was less than half of that observed.
  - Coarse resolution of multidecadal reanalysis data sets may overestimate wind drought amplitudes in complex terrain.

Research Need 5: Evaluation of accuracy of NSRDB, SARAH for WSDs.

- For solar, can also use radiative-transfer models that are driven only with satellite cloud observations.
  - National Solar Radiation Data Base (NSRBD), which predominantly covers North and South America
  - Surface Solar Radiation Data Set—Heliosat (SARAH), which covers Europe, Africa, and parts of the Middle East and South America
  - To date, I am not aware of any studies investigating the accuracy of NSRDB or SARAH for solar droughts.

Research Need 6: Evaluation of the impact of W&S flood events on system design and market design

High production periods are referred to as “floods,” where “flood” is used in the sense of a state of abundant flow or volume, which can have either positive or negative connotations

Floods present:

- opportunities for charging storage
- challenges for grid operations due to transmission congestion or curtailment of generation.
  - The largest 1-day flood events for different regions across the United States can exceed 300% of the long-term mean generation. Making use of that energy requires building infrastructure that would be used very rarely
- challenges for market design: are markets robust to long periods of negative prices that may occur during protracted flood events?

- **Research Need 7: Quantify the limits of predictability for WSDs**

- Simplest energy system model will use storage whenever generation < load and storage is not empty.

- If some dispatchable generation is available, can forecasts be used to develop more complex rules for discharging storage, to keep some available for most severe droughts?

- Important to know the limits of predictability of wind and solar droughts, of load extremes, and the limits of predictability for compound events combining all three. AI-model limits shorter or longer than NWP model?

- **Research Need 8: WSD implications for demand response programs**

- WSD statistics will influence the design of Demand Response programs, which will attempt to reduce WSD impacts by reducing concurrent demand.

- WSD drought predictability can also impact Demand Response programs. Forecasting power outages many days in advance makes Demand Response programs more attractive than if they occur with little warning.

Research Need 9: Climate sensitivity

Multiple studies have shown wind and solar mean generation sensitivity to various modes of climate variability (e.g. MJO, NAO, ENSO, PNA, PDO, AMO).

- Are WSDs also sensitive to climate modes of variability?
- How robust are these sensitivities across different geographical regions?
- How robust are the sensitivities to these modes of variabilities across different meteorological (reanalysis) data sets?

- How will the statistics of WSDs, and load, change under different climate change scenarios?
- Various studies have not found consistent results across climate models.

Research Need 10: Developing countries

- Climate change is a global issue
- Population and energy demand is growing rapidly in developing countries, and that is likely to continue
- Characterizing wind and solar droughts in developing countries is important in order to effectively design RE-based grids
- Likely that new observational networks will be needed to validate and correct model-based datasets.

Concluding remarks

- As electric grids become more renewables-based, those grids will become increasingly vulnerable to renewable energy droughts.

- Specific mitigation solutions will depend on the regional characteristics of WSDs: intensity, duration, spatial extent, and recurrence intervals. A better understanding of those drought characteristics is needed.

Thanks!